CHAPTER 7

Heavy Feedstock Refining—The Future

7.1 INTRODUCTION

With entry into the twenty-first century, petroleum refining technology is experiencing great innovation driven by the increasing supply of heavy feedstocks of decreasing quality and the fast increases in demand for clean and ultraclean vehicle fuels and petrochemical raw materials. As feedstocks to refineries change, there must be an accompanying change in refinery technology. This means a movement from conventional means of refining heavy feedstocks using (typically) coking technologies to more innovative processes (including hydrogen management) that will produce optimal amounts of liquid fuels from the feedstock and maintain emissions within environmental compliance (Davis and Patel, 2004; Penning, 2001; Speight, 2008, 2011a).

During the next 20–30 years, the evolution and future of heavy feedstock refining and the current refinery layout will be focused primarily on process modification with some new innovations coming onstream (Speight, 2007, 2011a). The industry will move predictably on to (i) deep conversion of heavy feedstocks, (ii) higher hydrocracking and hydrotreating capacity, and (iii) more efficient catalysts.

High conversion refineries will also move to gasification of feedstocks for the development of alternative fuels and to enhance equipment usage. A major trend in the refining industry market demand for refined products will be in synthesizing fuels from simple basic reactants (e.g., synthesis gas) when it becomes uneconomical to produce superclean transportation fuels through conventional refining processes. Fischer–Tropsch plants together with integrated gasification combined cycle (IGCC) systems will be integrated with or even into refineries, which will offer the advantage of high-quality products (Speight, 2013; Stanislaus et al., 2000).

This chapter presents suggestions and opinions on the means by which refinery processes will evolve during the next three-to-five decades. Material relevant to (i) comparisons of current feedstocks with
heavy oil and bio-feedstocks, (ii) evolution of refineries since the 1950s, (iii) properties and refinability of heavy oil and bio-feedstocks, (iv) thermal processes vs. hydroprocesses, and (v) evolution of products to match the environmental market, is presented.

7.2 REFINERY CONFIGURATIONS

A petroleum refinery is an industrial processing plant that is a collection of integrated process units (Gary et al., 2007; Hsu and Robinson, 2006; Speight, 2007; Speight and Ozum, 2002). The crude oil feedstock is typically a blend of two or more crude oils, often with heavy oil or even tar sand bitumen blended in to a maximum. With the depletion of known crude oil reserves, refining companies are seeking petroleum in places other than the usual sources of supply.

Hydrocarbon-based energy is important and energy prices have had an important effect on economic performance because energy is used directly and indirectly in the production of all goods and services and a decrease in the rate of increase in energy availability will have serious economic impacts.

7.2.1 Petroleum Refinery

The definition of crude oil is confusing and variable (Chapter 1) and has been made even more confusing by the introduction of other terms (Zittel and Schindler, 2007) that add little, if anything, to petroleum definitions and terminology (Speight, 2007, 2008).

In fact, there are different classification schemes based on (i) economic and/or (ii) geological criteria. For example, the economic definition of conventional oil is “conventional oil is oil which can be produced with current technology under present economic conditions.” The problem with this definition is that it is not very precise, and changes whenever the economic or technological aspects of oil recovery change. In addition, there are other classifications based on API gravity such as “conventional oil is crude oil having a viscosity above 17° API.” However, these definitions do not change the definition stated elsewhere (Chapter 1) that has been used throughout this book.

In recent years, the average quality of crude oil has deteriorated and continues to do so as more heavy oil and tar sand bitumen are sent to refineries (Speight, 2007, 2008, 2011). This has changed the
nature of crude oil refining considerably. Indeed, the declining reserves of lighter crude oil have resulted in an increasing need to develop options to desulfurize and upgrade the heavy feedstocks, specifically heavy oil and bitumen. This has resulted in a variety of process options that specialize in sulfur removal during refining.

In addition, the general trend throughout refining has been to produce more products from each barrel of petroleum and to process those products in different ways to meet the product specifications for use in modern engines. Overall, the demand for gasoline has rapidly expanded and demand has also developed for gas oils and fuels for domestic central heating, and fuel oil for power generation, as well as for light distillates and other inputs, derived from crude oil, for the petrochemical industries.

As the need for the lower boiling products developed, petroleum yielding the desired quantities of the lower boiling products became less available and refineries had to introduce conversion processes to produce greater quantities of lighter products from the higher boiling fractions. The means by which a refinery operates in terms of producing the relevant products depends not only on the nature of the petroleum feedstock but also on its configuration (i.e., the number of types processes that are employed to produce the desired product slate), and the refinery configuration is, therefore, influenced by the specific demands of a market.

Therefore, refineries need to be constantly adapted and upgraded to remain viable and responsive to ever-changing patterns of crude supply and product market demands. As a result, refineries have been introducing increasingly complex and expensive processes to gain higher yields of lower boiling products from the heavy feedstocks.

Finally, the yield and quality of refined petroleum products produced by any given oil refinery depend on the mixture of crude oil used as feedstock and the configuration of the refinery facilities. Light/sweet crude oil is generally more expensive and has inherent high yields of higher value, low boiling products such as naphtha, gasoline, jet fuel, kerosene, and diesel fuel. Heavy sour crude oil is generally less expensive and produces greater yields of lower value, higher boiling products that must be converted into lower boiling products.
The configuration of refineries may vary from refinery to refinery. Some refineries may be more oriented toward the production of gasoline (large reforming and/or catalytic cracking) whereas the configuration of other refineries may be more oriented toward the production of middle distillates such as jet fuel and gas oil.

Changes in the characteristics of conventional crude oil can be exogenously specified and will trigger changes in refinery configurations and corresponding investments. In the future, crude slate is expected to consist of larger fractions of both heavier, sourer crudes and extra-light inputs, such as natural gas liquids (NGLs). There will also be a shift toward bitumen, such as Canadian oil sands and Venezuelan heavy oil. These changes will require investment in upgrading, either at field level to process tar sand bitumen and oil shale into synthetic crude oil shale or at the refinery level (Speight, 2011a).

There are currently four ways of bringing heavy feedstocks to market (Hedrick et al., 2006).

First, the heavy feedstock may be (partially or fully) upgraded in the oil field, leaving much of the material behind as coke, and the upgraded material will then be sent by pipeline as synthetic crude oil. With this method, the crude is fractionated and the residue is coked—the products of the coking operation, and in some cases some of the residue, may also be hydrotreated in a field unit. The hydrotreated materials are recombined with the fractionated light materials to form synthetic crude that is then transported to market in a pipeline. Examples of this type of processing can be seen in the current Canadian oil sands operations around Fort McMurray in Alberta, Canada (Speight, 2007, 2008, 2011a). This option can be made more workable by the presence of abundant supplies of natural gas in the area as well a local electrical power source.

Second, there is also an option to build upgrading facilities at an established port area with abundant gas and electric resources. The liquid products from a coking operation can be hydrotreated and mixed back with the virgin materials. A pipeline from the complex to the oil field transports cutter stock to the oil field in sufficient quantity to produce pipeline-acceptable crude from the virgin heavy feedstocks. There are several examples of this kind of facility located in the Jose,
Venezuela, area that enable the production of heavy crude from the Orinoco River Basin.

Third, it is also common practice to use conventional crude oil which is located in the general area to dilute the heavy feedstock to produce an acceptable pipeline material. While a seemingly viable option on paper, this option has a number of limitations. For example, the heavy feedstock production could be limited by the amount of conventional crude oil that is available for dilution. Another problem is compatibility—the conventional crude oil and the heavy feedstock may have limited compatibility which would limit the amount of dilution and the amount of heavy feedstock produced (Speight, 2007, 2011a).

The fourth and final solution is closely related to the established port area solution where a substantial oil field is located far from other fields, from power or from natural gas. This solution includes building a reverse pipeline from a refinery to the oil field as well as a crude pipeline.

There is also the need for a refinery to be configured to accommodate opportunity crude oils and/or high acid crude oils (Chapter 1) which, for the purpose of this text, are included here with the heavy feedstocks.

Opportunity crude oils are often dirty and need cleaning before refining by removal of undesirable constituents such as high-sulfur, high-nitrogen, and high-aromatics (such as polynuclear aromatic) components. A controlled visbreaking treatment would clean up such crude oils by removing these undesirable constituents (which, if not removed, would cause problems further down the refinery sequence) as coke or sediment.

On the other hand, high acid crude oils cause corrosion in the atmospheric and vacuum distillation units. In addition, overhead corrosion is caused by the mineral salts, such as magnesium, calcium, and sodium chloride, which are hydrolyzed to produce volatile hydrochloric acid, causing high corrosion conditions in the overhead exchangers. Therefore, these salts present significant contamination in opportunity crude oils. Other contaminants in opportunity crude oils which are
shown to accelerate the hydrolysis reactions, are inorganic clays and organic acids.

In addition to taking preventative measures to enable the refinery to process these heavy feedstocks without serious deleterious effects on the equipment used, refiners will need to develop programs for detailed and immediate feedstock assessment so that they can determine the quality of a crude oil very quickly and so that it can be evaluated appropriately and management of the crude processing planned meticulously.

7.2.2 Gasification Refinery

In addition to the conventional petroleum refinery, installation of a gasification unit would offer a technology not currently available in a nongasification refinery operation. The refinery would produce synthesis gas (from the heavy feedstock) from which liquid fuels would be manufactured using Fischer–Tropsch synthesis technology (Speight, 2011b, 2013).

Synthesis gas (syngas) is the name given to a gas mixture that contains varying amounts of carbon monoxide and hydrogen generated by the gasification of a carbon-containing fuel to a gaseous product with a heating value. Examples include the gasification of coal or heavy feedstocks (Speight, 2008, 2011a). Synthesis gas is used as a source of hydrogen or as an intermediate in producing hydrocarbons via Fischer–Tropsch synthesis. Heavy feedstock and biomass co-gasification is therefore one of the most technically and economically convincing energy provision possibilities for a potentially carbon-neutral economy.

A modified version of steam reforming known as auto-thermal reforming, which is a combination of partial oxidation near the reactor inlet with conventional steam reforming further along the reactor, improves the overall reactor efficiency and increases the flexibility of the process. Partial oxidation processes using oxygen instead of steam have also found wide application for synthesis gas manufacture, with the special feature that they could utilize low-value heavy feedstocks. In recent years, catalytic partial oxidation employing very short reaction times (milliseconds) at high temperatures (850–1000°C) is providing still another approach to synthesis gas manufacture.
As heavy feedstock supplies increase, the desirability of producing gas from other carbonaceous feedstocks will increase, especially in those areas where natural gas is in short supply. It is also anticipated that costs of natural gas will increase, allowing coal gasification to compete as an economically viable process.

7.2.2.1 Gasifier Types
A gasifier differs from a combustor in that the amount of air or oxygen available inside the gasifier is carefully controlled so that only a relatively small portion of the fuel burns completely. The partial oxidation process provides the heat and, rather than combustion, most of the carbon-containing feedstock is chemically broken apart by the heat and pressure applied in the gasifier resulting in the chemical reactions that produce synthesis gas. However, the composition of the synthesis gas will vary because of dependence upon the conditions in the gasifier and the type of feedstock.

Four types of gasifiers are currently available for commercial use: (i) the countercurrent fixed bed, (ii) the co-current fixed bed, (iii) the fluidized bed, and (iv) the entrained flow (Speight, 2008, 2013).

The countercurrent fixed-bed (up draft) gasifier consists of a fixed bed of carbonaceous fuel through which the gasification agent (steam, oxygen, and/or air) flows in countercurrent configuration. The ash is either removed dry or as a slag. The nature of the gasifier means that the fuel must have high mechanical strength and must be noncaking so that it will form a permeable bed, although recent developments have reduced these restrictions to some extent. The throughput for this type of gasifier is relatively low. Thermal efficiency is high as the gas exit temperatures are relatively low and, as a result, tar and methane production is significant at typical operation temperatures, so product gas must be extensively cleaned before use or recycled to the reactor.

The co-current fixed-bed (down draft) gasifier is similar to the countercurrent type, but the gasification agent gas flows in co-current configuration with the fuel (downward, hence the name down draft gasifier). Heat needs to be added to the upper part of the bed, either by combusting small amounts of the fuel or from external heat sources. The produced gas leaves the gasifier at a high temperature, and most of this heat is often transferred to the gasification agent added in the top of the bed. Since all tars must pass through a hot bed of char in
this configuration, tar levels are much lower than for the countercurrent type.

In the fluidized-bed gasifier, the fuel is fluidized in oxygen (or air) and steam. The temperatures are relatively low in dry ash gasifiers, so the fuel must be highly reactive; low-grade coals are particularly suitable. The agglomerating gasifiers have slightly higher temperatures, and are suitable for higher rank coals. Fuel throughput is higher than for the fixed bed, but not as high as for the entrained flow gasifier. The conversion efficiency is typically low, so recycle or subsequent combustion of solids is necessary to increase conversion. Fluidized-bed gasifiers are most useful for fuels that form highly corrosive ash that would damage the walls of slagging gasifiers. The ash is removed dry or as heavy agglomerates—a disadvantage of biomass feedstocks is that they generally contain high levels of corrosive ash.

In the entrained-flow gasifier a dry pulverized solid, an atomized liquid fuel, or a fuel slurry is gasified with oxygen (much less frequent: air) in co-current flow. The high temperatures and pressures also mean that a higher throughput can be achieved but thermal efficiency is somewhat lower as the gas must be cooled before it can be sent to a gas processing facility. All entrained flow gasifiers remove the major part of the ash as a slag as the operating temperature is well above the ash fusion temperature. Biomass can form slag that is corrosive for ceramic inner walls that serve to protect the gasifier’s outer wall.

Gasification also offers more scope for recovering products from waste than incineration. When waste is burnt in an incinerator the only practical product is energy, whereas the gases, oils, and solid char from pyrolysis and gasification can not only be used as a fuel but also purified and used as a feedstock for petrochemicals and other applications. Many processes also produce a stable granulate (instead of an ash) which can be more easily and safely utilized. In addition, some processes are targeted at producing specific recyclables such as metal alloys and carbon black. From waste gasification, in particular, it is feasible to produce hydrogen, which many see as an increasingly valuable resource.

### 7.2.2.2 Fischer–Tropsch Synthesis

The synthesis reaction is dependent on a catalyst, mostly an iron or cobalt catalyst whereon the reaction takes place. There is either a
low- or high-temperature process (LTFT and HTFT), with temperatures ranging between 200°C and 240°C for LTFT and between 300°C and 350°C for HTFT. The HTFT uses an iron catalyst, and the LTFT either an iron or a cobalt catalyst. The different catalysts include also nickel-based and ruthenium-based catalysts, which also have enough activity for commercial use in the process.

The reactors are the *multitubular fixed bed*, the *slurry*, or the *fluidized-bed* (with either fixed or circulating bed) reactor. The fixed-bed reactor consists of thousands of small tubes with the catalyst as surface-active agent in the tubes. Water surrounds the tubes and regulates the temperature by settling the pressure of evaporation. The slurry reactor is widely used and consists of fluid and solid elements, where the catalyst has no particular position but flows around as small pieces of catalyst together with the reaction components. The slurry and fixed-bed reactors are used in LTFT. The fluidized-bed reactors are diverse, but characterized by the fluid behavior of the catalyst.

*High-temperature* Fischer–Tropsch technology uses a fluidized catalyst at 300–330°C. Originally circulating fluidized-bed units were used (Synthol reactors). Since 1989 a commercial scale classical fluidized-bed unit has been implemented and improved upon.

*Low-temperature* Fischer–Tropsch technology was originally used in tubular fixed-bed reactors at 200–230°C. This produces a more paraffinic and waxy product spectrum than the *high-temperature* technology. A new type of reactor (the Sasol slurry phase distillate reactor) has developed and is in commercial operation. This reactor uses a slurry phase system rather than a tubular fixed-bed configuration and is currently the favored technology for the commercial production of synfuels.

### 7.3 THE FUTURE REFINERY

Over the past four decades, the refining industry has been challenged by changing feedstocks and product slate. In the near future, the refining industry will become increasingly flexible with improved technologies and improved catalysts for refining heavy feedstocks. The main technological progress will be directed to heavy feedstock upgrading,
cleaner transportation fuel production, and the integration of refining and petrochemical businesses (Speight, 2011a).

As outlined elsewhere (Chapters 2–6), even the tried and true processes will see changes as they evolve.

Thermal processes (Chapter 2) will also evolve and become more efficient. While the current processes may not see much change in terms of reactor vessel configuration, there will be changes to the internal parts of the reactor and to the nature of the catalysts. For example, the tried and true coking processes will remain the mainstay of refineries coping with an influx of heavy feedstocks, but other process options will be used.

For example, visbreaking (or even hydrovisbreaking—i.e., visbreaking in an atmosphere of hydrogen or in the presence of a hydrogen donor material) (Chapter 2), the long ignored step-child of the refining industry, may see a surge in use as a pretreatment process for heavy feedstock upgrading. Management of the process to produce a liquid product that has been freed of the high potential for coke deposition (by taking the process parameters into the region where sediment forms) either in the absence or in the presence of, for example, a metal oxide scavenger could be a valuable ally to catalyst cracking or hydrocracking units.

In the integration of refining and petrochemical businesses, new technologies based on the traditional fluid catalytic cracking process (Chapter 3) will be of increased interest to refiners because of their potential to meet the increasing demand for light olefins. Meanwhile, hydrocracking, due to its flexibility, will take the central position in the integration of refining and petrochemical businesses in the twenty-first century. Alternately, operating the catalytic cracking unit solely as a slurry riser cracker (without the presence of the main reactor) followed by separation of coke (sediment) would save the capital outlay required for a new catalytic cracker and might even show high conversion to valuable liquids. The quality (i.e., boiling range) of the distillate would be dependent upon the residence time of the slurry in the pipe.

Scavenger additives such as metal oxides may also see a surge in use. As a simple example, a metal oxide (such as calcium oxide) has
the ability to react with sulfur-containing feedstock to produce a hydrocarbon (and calcium sulfide):

\[ \text{Heavy feedstock}[S] + \text{CaO} \rightarrow \text{hydrocarbon product} + \text{CaS} + \text{H}_2\text{O} \]

Propane has been used extensively in deasphalting heavy feedstocks (Chapter 6), especially in the preparation of high-quality lubricating oils and feedstocks for catalytic cracking units (Speight, 2007). The use of propane has necessitated elaborate solvent cooling systems utilizing cooling water, which is a relatively expensive cooling agent. In order to circumvent such technology, future heavy feedstock processing units will use solvent systems that will allow operation at elevated temperatures relative to conventional propane deasphalting temperatures, thereby permitting easy heat exchange. This will require changes to the solvent composition and the inclusion of solvents not usually considered to be deasphalting solvents.

Furthermore, as a means of energy reduction for the process, in future deasphalting units the conventional solvent recovery scheme will be retrofitted with a supercritical solvent recovery scheme (Chapter 6) to reap the benefits of higher energy efficiency. Other improvements will include variations in the internal parts of the extraction column.

The increasing focus on reducing sulfur content in fuels will ensure that the role of desulfurization in the refinery increases in importance (Babich and Moulijn, 2003). Currently, the process of choice is the hydrotreater, in which hydrogen is added to the fuel to remove the sulfur from the fuel. Some hydrogen may be lost to reduce the octane number of the fuel, which is undesirable.

Because of the increased attention on fuel desulfurization various new process concepts are being developed with various claims of efficiency and effectiveness. The major developments in desulfurization will be three main routes: (i) advanced hydrotreating (new catalysts, catalytic distillation, processing at mild conditions), (ii) reactive adsorption (type of adsorbent used, process design), and (iii) oxidative desulfurization (catalyst, process design) (Chapter 4).

Heavy feedstock hydrotreating (Chapter 4) requires considerably different catalysts and process flows, depending on the specific operation so that efficient hydroconversion through uniform distribution of
liquid, hydrogen-rich gas, and catalyst across the reactor is assured. In addition to an increase in guard bed use (Chapters 4 and 5), the industry will see an increase in automated demetallization of fixed-bed systems as well as more units that operate as ebullating-bed hydrocrackers.

For heavy feedstock upgrading, hydrotreating technology (Chapter 4) and hydrocracking technology (Chapter 5) will be the processes of choice. For cleaner transportation fuel production, the main task is the desulfurization of gasoline and diesel. With the advent of various techniques, such as adsorption and biodesulfurization, future development will be still focused on hydrodesulfurization techniques.

In fact, hydrocracking (Chapter 5) will continue to be an indispensable processing technology to the modern petroleum refining and petrochemical industry due to its flexibility in relation to feedstocks and product schema and output of high-quality products. In particular, high-quality naphtha, jet fuel, diesel, and lube base oil can be produced through this technology. The hydrocracker provides a better balance of gasoline and distillates, improves gasoline yield and octane quality, and can supplement the fluid catalytic cracker to upgrade heavy feedstocks. In the hydrocracker, light fuel oil is converted into lighter products under a high hydrogen pressure and over a hot catalyst bed—the main products are naphtha, jet fuel, and diesel oil.

For the heavy feedstocks (and even for bio-feedstocks), which will increase in amount in terms of hydrocracking feedstocks, reactor designs will continue to focus on online catalyst addition and withdrawal (Chapter 5). Fixed-bed designs have suffered from (i) mechanical inadequacy when used for the heavier feedstocks and (ii) short catalyst lives—6 months or less—even though large catalyst volumes are used (liquid hourly space velocity (LHSV) typically of 0.5—1.5). Refiners will attempt to overcome these shortcomings by innovative designs, allowing better feedstock flow and catalyst utilization or online catalyst removal. For example, the onstream catalyst replacement process, in which a lead, moving-bed reactor is used to demetalized heavy feed ahead of the fixed-bed hydrocracking reactors, will find increased use but whether this will be adequate for continuous hydrocracking heavy feedstocks remains a question.
Catalyst development for the various catalytic and hydrogen-related processes (Chapters 3—5) will be key in the modification of processes and the development of new ones to make environmentally acceptable fuels (Rostrup-Nielsen, 2004). Innovations have already occurred in catalyst materials which have allowed refiners to vastly improve environmental performance, product quality and volume, feedstock flexibility, and energy management without fundamentally changing fixed capital stocks. Advanced design and manufacturing techniques mean that catalysts can now be formulated and manufactured for specific processing units, feedstocks, operating environments, and finished product slates.

The panacea (rather than a Pandora’s Box) for heavy feedstocks could well be the gasification refinery (Speight, 2011a). Furthermore, the integration of gasification technology into a refinery offers alternate processing options for heavy feedstocks. The refinery of the future will have a gasification section devoted to the conversion of coal and biomass to Fischer–Tropsch hydrocarbons—perhaps even with rich oil shale added to the gasifier feedstock. Many refineries already have gasification capabilities but the trend will increase to the point (over the next two decades) where nearly all refineries will feel the need to construct a gasification section to handle heavy feedstocks.

The demand for high-value petroleum products will maximize production of transportation fuels. Hydroprocessing heavy feedstocks will be widespread rather than appearing in selected refineries (Rana et al., 2007). At the same time, hydrotreated heavy feedstocks will be the common feedstocks for fluid catalytic cracking units—additional conversion capacity will be necessary to process increasingly heavier feedstocks. Other challenges facing the refining industry include its capital-intensive nature and dealing with the disruptions to business operations that are inherent in industry. It is imperative for refiners to raise their operations to new levels of performance. Merely extending current performance incrementally will fail to meet most companies’ performance goals.

To circumvent these issues, there may be no way out for energy producers other than to consort to using alternative energy sources with petroleum, and not to oppose this trend. This leads to the concept of alternative energy systems, which is wider ranging and more
meaningful than *alternative energy sources*, because it relates to the actual transformation process of the global energy system (Szklo and Schaeffler, 2005). Alternative energy systems integrate petroleum with other energy sources and pave the way for new systems where *refinery flexibility* will be a key target, especially when related to the increased use of renewable energy sources.

**REFERENCES**


